Surrogate Nuclear Reactions
The Theory Effort at LLNL

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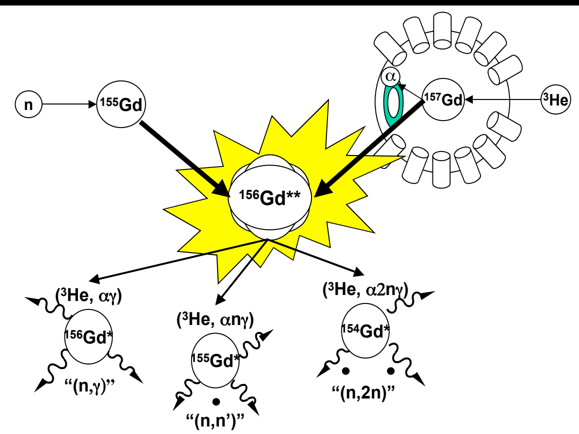

The LLNL team:
L.Ahle, L. Bernstein, C. Britt, D. Brown, J. Church, J. Cooper, F. Dietrich, J. Escher, C. Forssén, R. Hoffman, W. Younes, …

"Nuclear Reactions on Unstable Nuclei and the Surrogate Reaction Technique"
Asilomar, Pacific Grove, California
January 12-15, 2004

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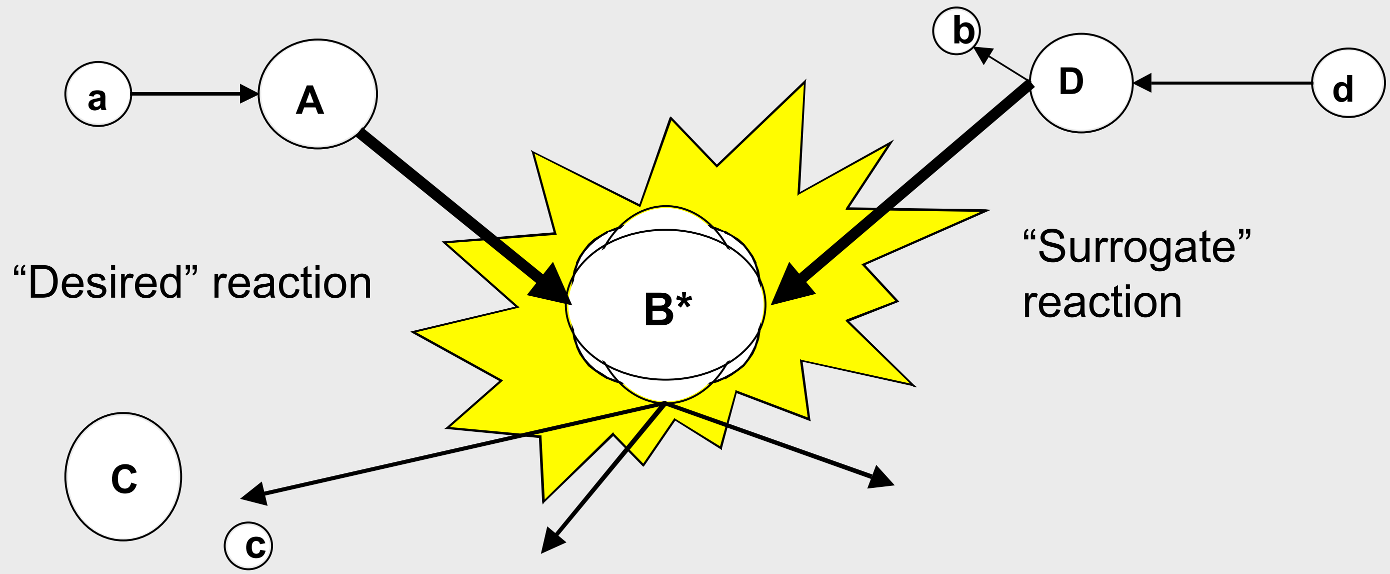
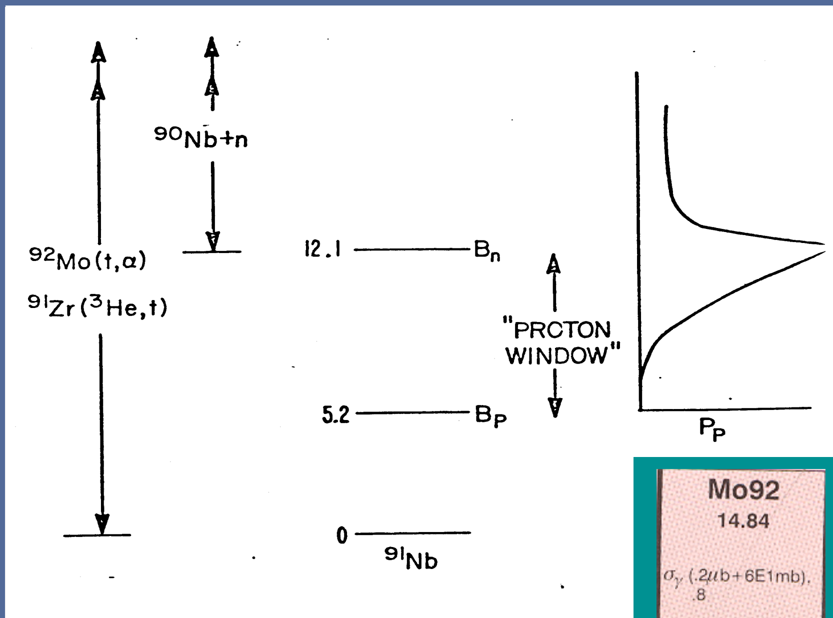
The Surrogate concept

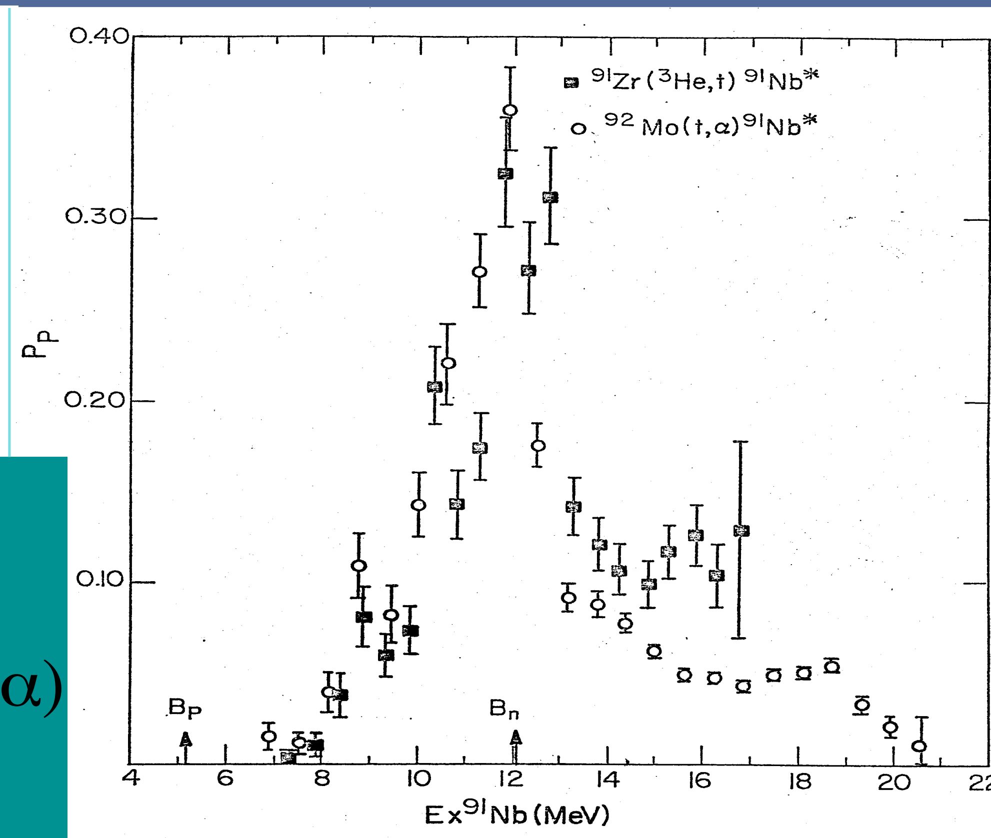
The problem: Many interesting reactions cannot be measured because they involve unstable or hard-to-produce targets.
Realization: Many of these reactions are 2-step reactions that proceed through an intermediate compound nucleus.



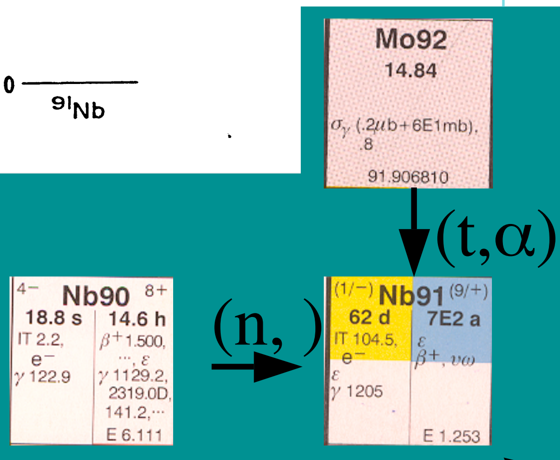
The Surrogate idea: Form the compound nucleus via a Surrogate reaction. Combine the measured decay probabilities with the calculated cross section for forming the compound system in the 'desired reaction'.

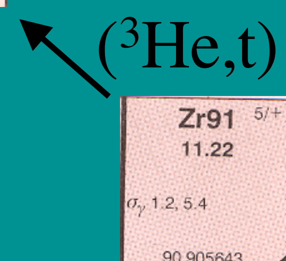
The Surrogate technique in its infancy - the mass~90 region





Early studies

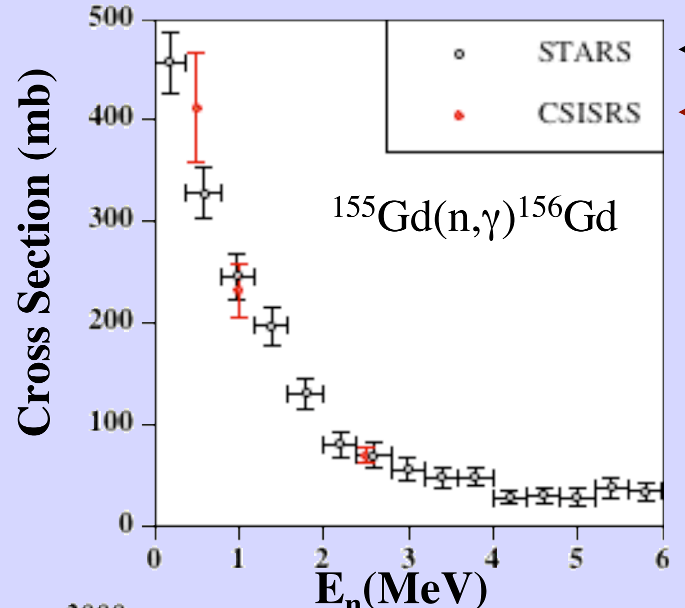


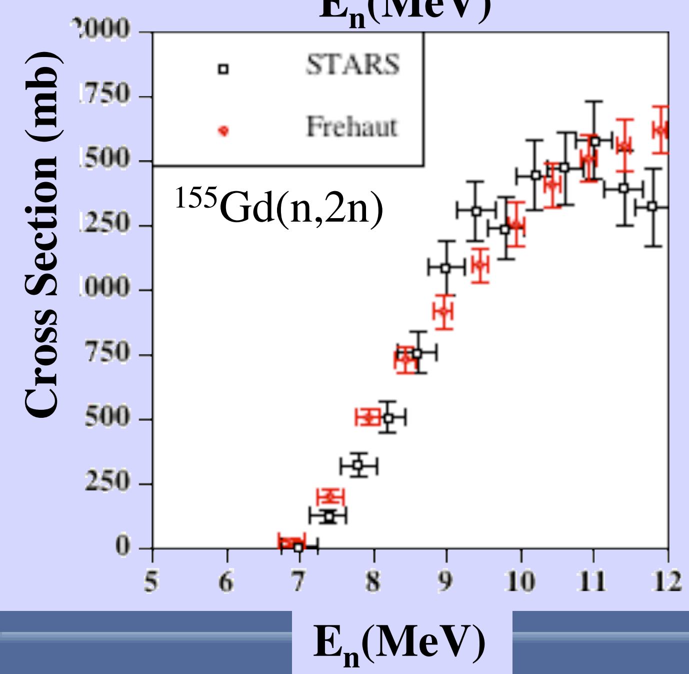


Britt and Wilhelmy,
Progress Report, Nov. 1976,
Wilhelmy's presentation,
this workshop

^{91}Zr(^{3}He,t)^{91}Nb* and ^{92}Mo(t,α)^{91}Nb* as Surrogates for ^{90}Nb(n,)^{91}Nb* -> p + ^{90}Zr

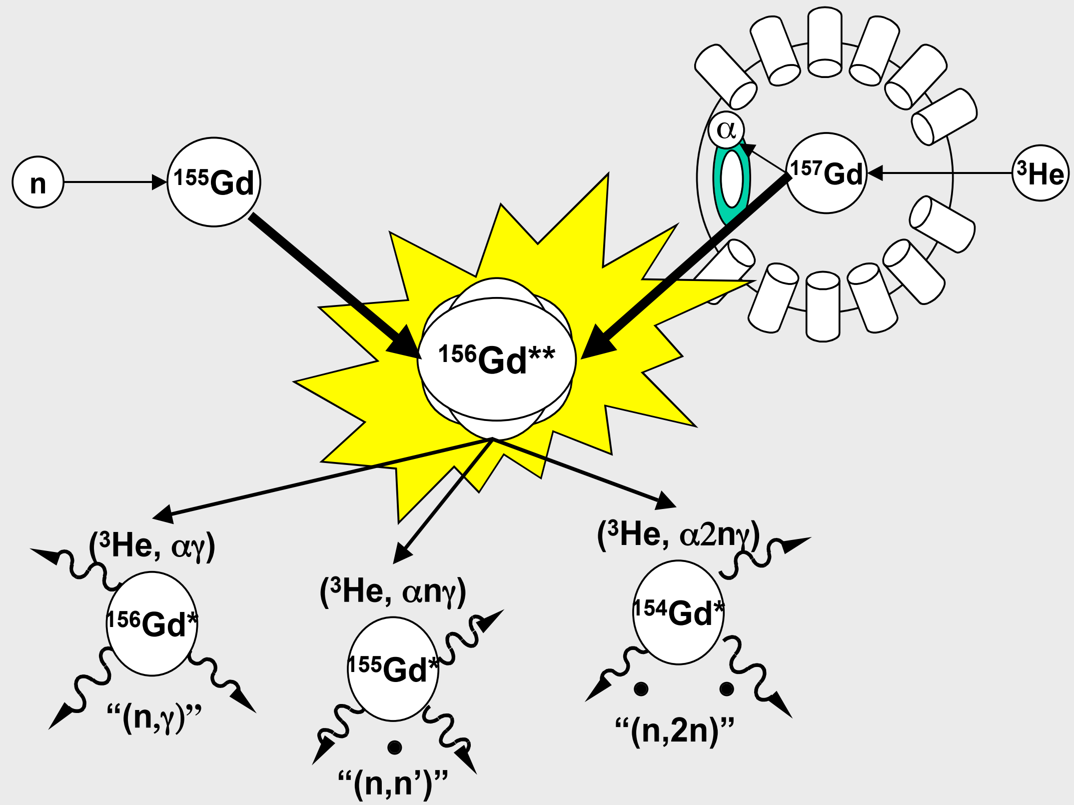
The Surrogate technique reconsidered - rare earth nuclei





← Surrogate measurement using ^{157}Gd(^{3}He,α)

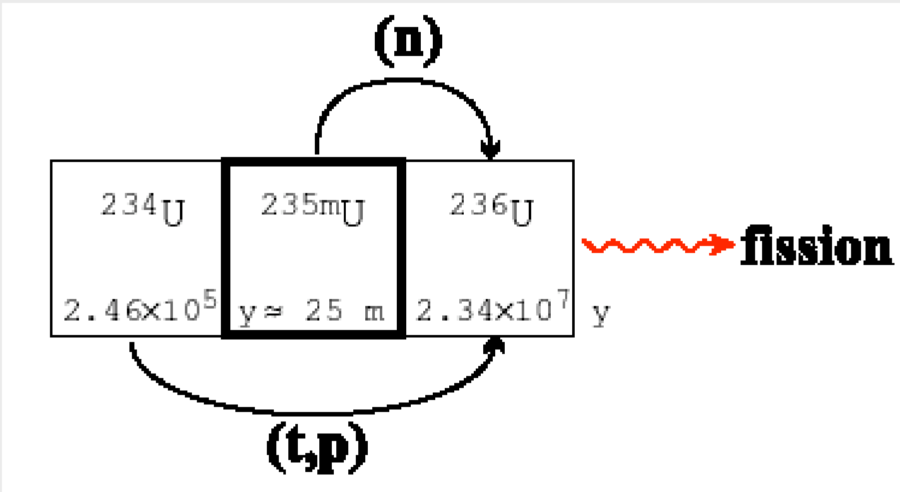
← Direct measurement

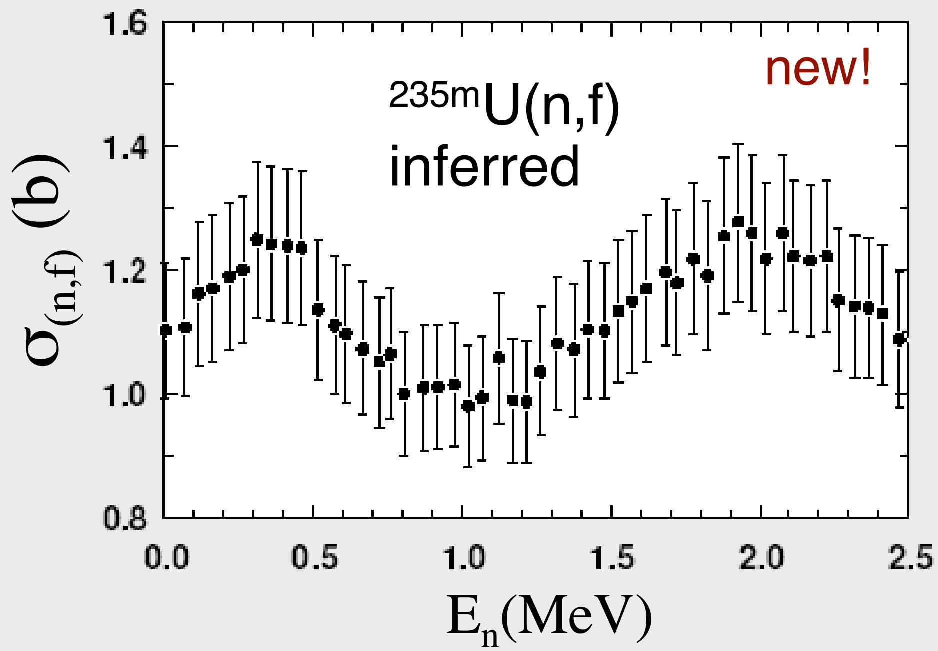


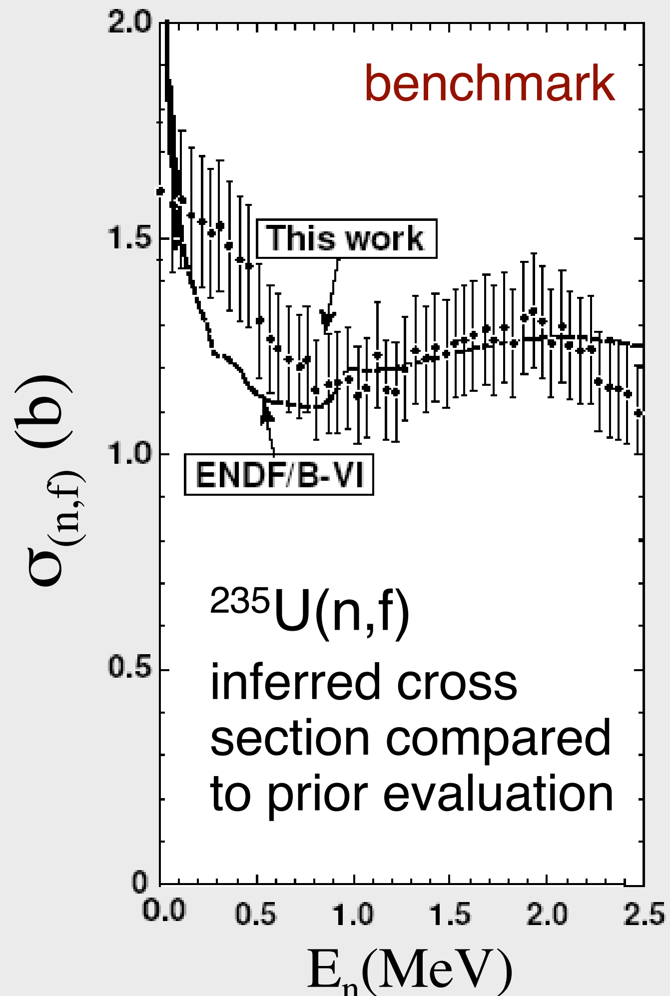
Bernstein *et al.*, analysis in progress

Experiment carried out in Berkeley

The Surrogate technique carefully and successfully revisited - actinide nuclei





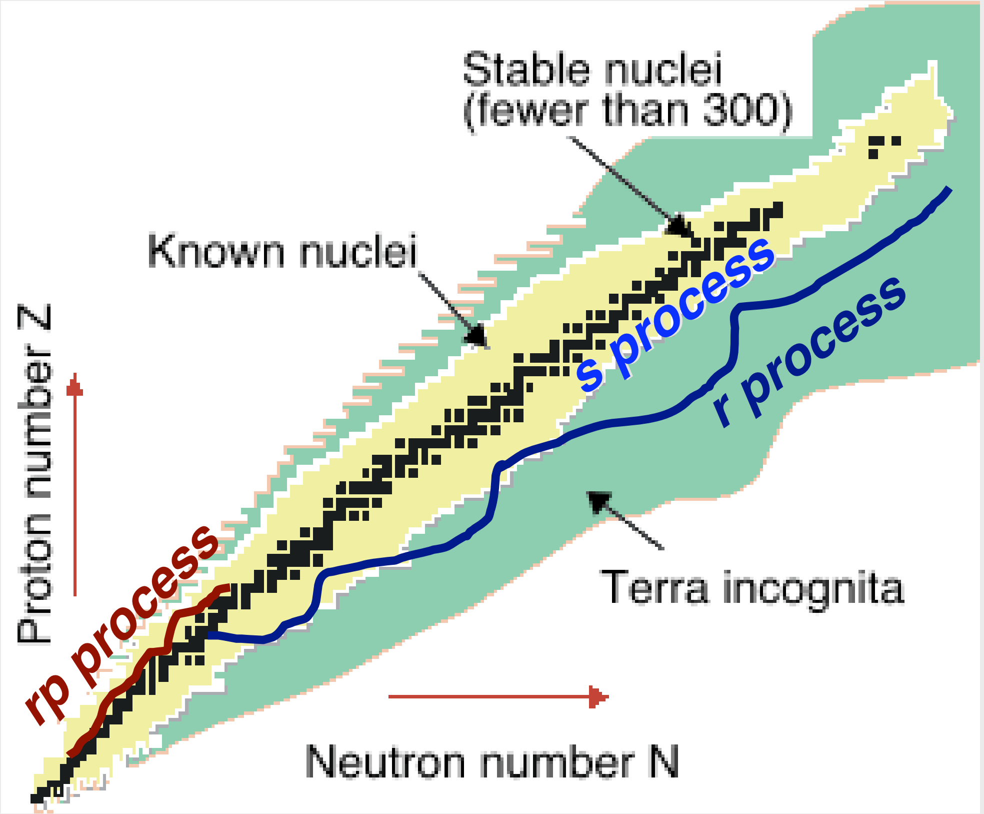


Younes & Britt,
PRC 67 (2003) 024610,
PRC 68 (2003) 034610

Where do we want to apply the Surrogate approach?

The Surrogate technique might be very useful for

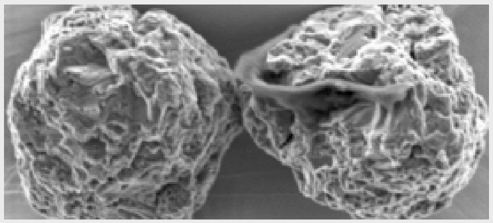
- understanding reactions on a variety of unstable nuclei
- obtaining new insights into astrophysical processes



Disentangling the s and r processes…

Generally…

- **s process better known than r process**
- **r process abundances are obtained by subtracting s process contributions from measured total abundances**



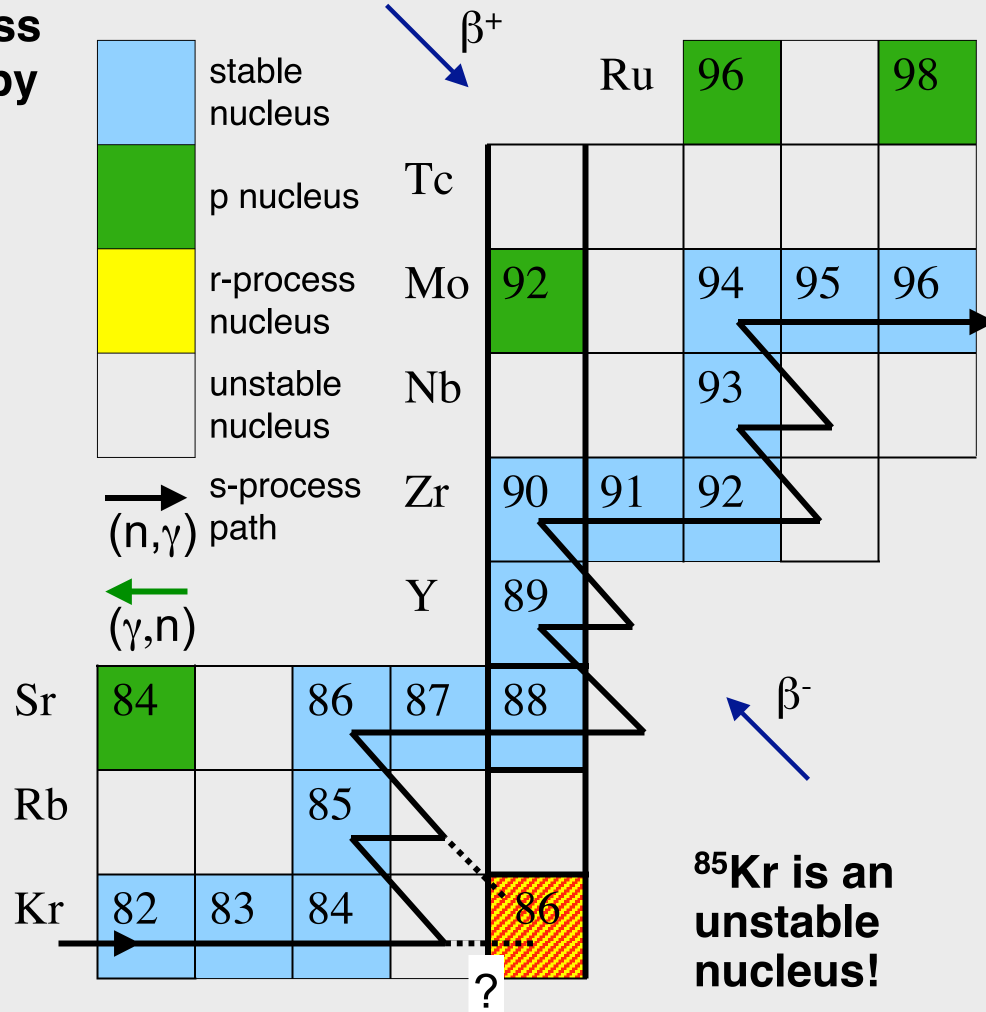
Presolar grains from the Murchison meteorite. Grains provide information on abundance distributions.

Reliable s-process abundances are required to shed light on the issue!

What is the cross section for:

n + ^{85}Kr --> ^{86}Kr* + γ ?

Synthesis of elements in the A=90 region



^{85}Kr is an unstable nucleus!

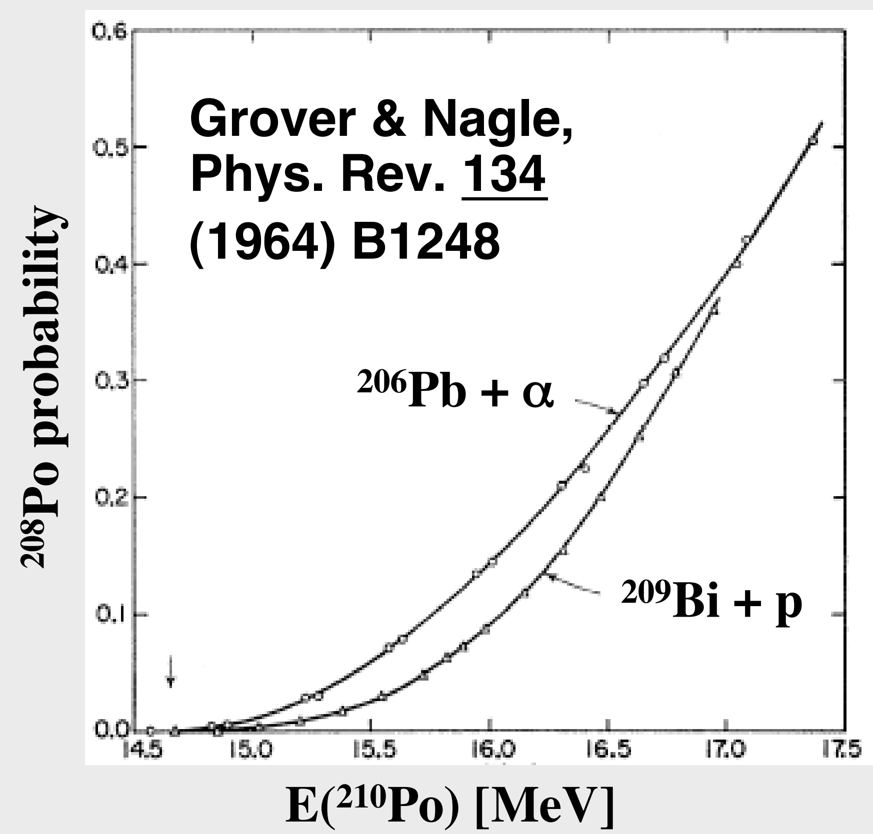
…requires knowledge of reactions on unstable nuclei!

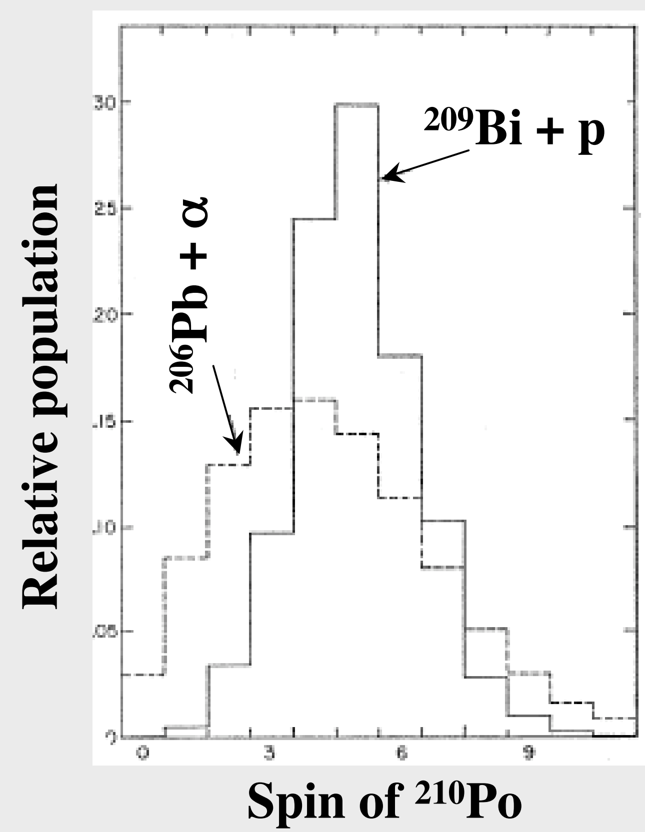
Developing the framework…
Considerations, concerns, and challenges

Different reactions, same results?

Even a compound nucleus remembers constants of motion!

A compound nucleus can often be formed in two (or more) ways.
How do the constants of motion differ in the different entrance channels?
How do these differences impact the observed cross sections?





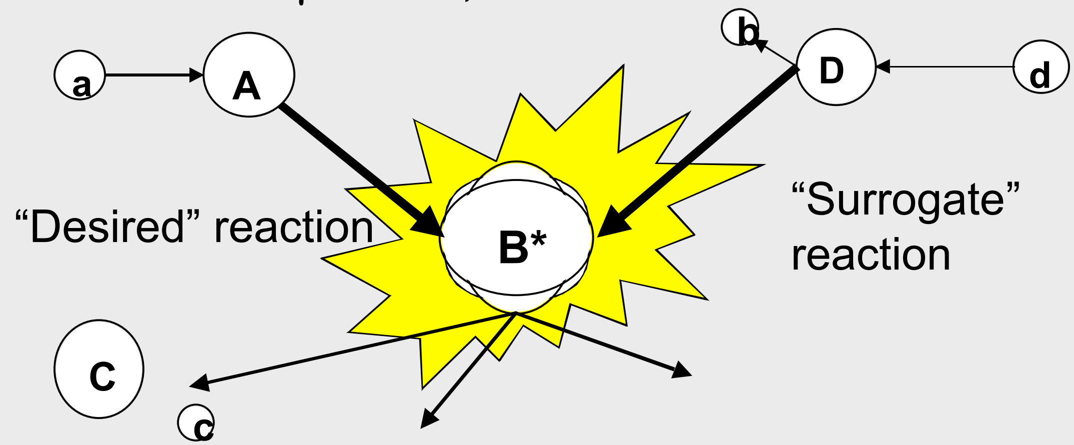
Challenge 1: Angular-momentum matching

"Simple life":

Cross section for two-step process: $\sigma_{\alpha\gamma} = \sigma_\alpha^{CN}(E) \cdot G^{CN}_\gamma(E)$

$\sigma_\alpha^{CN}(E) = \sigma(a+A\text{->}B^*)$ - can be calculated

$G^{CN}_\gamma(E)$ - probability for decay into channel γ = c+C, can be determined from Surrogate experiments



"Real life":

Cross section for a+A -> B* -> c+C : $\sigma_{\alpha\gamma} = \Sigma_{J,\pi}\, \sigma_\alpha^{CN}(E,J,\pi) \cdot G^{CN}_\gamma(E,J,\pi)$

J - angular momentum of compound nucleus B*

$\sigma_\alpha^{CN}(E,J,\pi)$ can be calculated

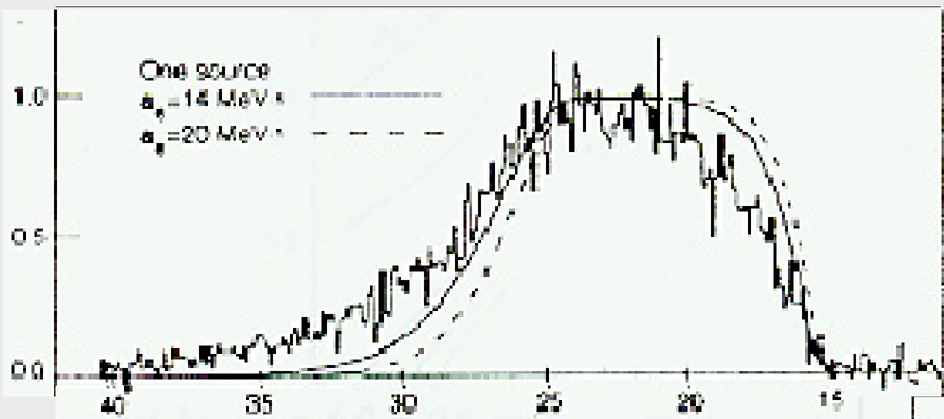
Problem: experiments only determine $\mathcal{P}(E) = \Sigma_{J,\pi}\, P_\delta^{CN}(E,J,\pi) \cdot G^{CN}_\gamma(E,J,\pi)$

--> Nuclear theory is needed to extract the individual $G^{CN}_\gamma(E,J,\pi)$.

Formation and decay of the intermediate nucleus

Central point

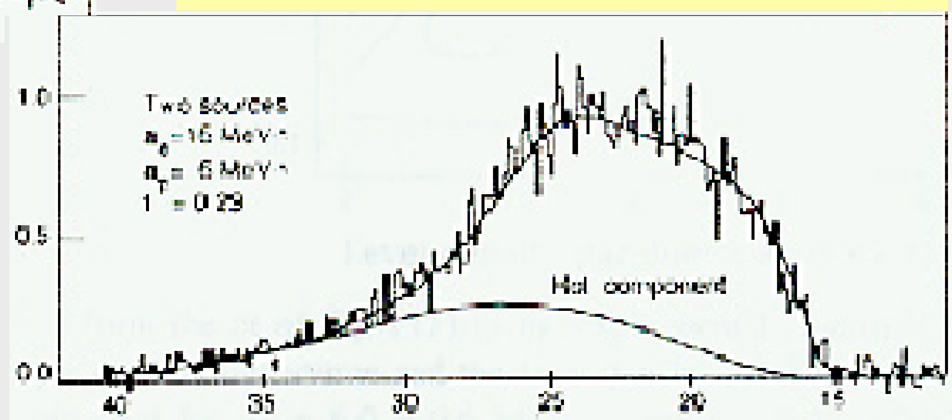
Formation and decay of a true compound nucleus are independent of each other. The Surrogate method assumes that the intermediate nucleus is in a compound state, i.e. equilibrated, before it decays.



Assuming equilibrated ^{162}Dy

α-energy probabilities for ^{163}Dy(^{3}He,α2n)^{160}Dy

With pre-equilibrium contributions



Guttormsen *et al.*, NPA 587 (1995) 401

Challenge 2: The role of the compound nucleus

Central point

Formation and decay of a true compound nucleus are independent of each other. The Surrogate method assumes that the intermediate nucleus is in a compound state, i.e. equilibrated, before it decays.

Tasks

- Study the formation of the intermediate nucleus via various direct reactions and estimate the probability that pre-equilibrium decay occurs.

  (Experiments can look for high-energy particles emitted from the decaying system that are inconsistent with the formation of a compound nucleus.)

- Develop systematics to determine suitable kinematic ranges.

- Determine which Surrogate reactions are most suitable for forming the compound nucleus of interest.

--> Theory is needed for separating out pre-equilibrium effects.

LDRD project at LLNL - theory interacting with experiment

Talks by J. Church and C. Plettner

1) Resolve the angular-momentum issue

> Measure and analyze $^{92}Zr(^{3}He,\alpha)^{91}Zr$, a Surrogate for $^{90}Zr(n,\gamma)^{91}Zr$.

-> Experiment completed, analysis in progress.

> Develop models to incorporate angular-momentum distributions. Test the models.

2) Apply the new formalism to various interesting cases

> Measure and analyze a Surrogate for $^{85}Kr(n,\gamma)^{86}Kr$, e.g. $^{86}Kr(\alpha,\alpha')^{86}Kr$.

> Measure and analyze further reactions, e.g. $^{48}V(n,p)^{48}Ti$ via $^{49}Ti(^{3}He,t)^{49}V$.

3) Extend the theory

> Study the feasibility of using Surrogates to determine (p,γ) cross sections on unstable nuclei in the A=60-90 region.

4) Study compound nucleus formation

> Study the formation of the intermediate nucleus via various direct reactions. Study the role of pre-equilibrium contributions.

> Carry out and analyze relevant experiments.

Further challenges

Although the planned work addresses several important issues, there are additional significant challenges that need to be considered:

- Optical model: How do the optical model parameters change as one moves away from stability? What are the fundamental limitations of the optical model?
- Level densities: Major improvements necessary (level densities needed in various energy ranges, for various deformations,...)! How do level densities change as one moves away from stability?
- Direct reactions populating states in the continuum
- Descriptions of multi-particle transfers
- Models for fission
- Etc.

Suggestions for discussions

1. **Matching entrance and exit channels:** A compound nucleus can often be formed in two (or more) ways. How do the constants of motion (energy, angular momentum, parity, isospin, etc.) differ from each other in the different entrance channels? How do these differences impact the observed cross sections? Is it possible to extract reliable branching ratios for the decay of the compound nucleus into different exit channels? What experimental data can be provided to help match the entrance and exit channels?

2. **Pre-equilibrium effects:** A central issue in the Surrogate approach is the assumption that a compound nucleus is formed which then decays into various possible exit channels. This assumption has to revisited. In particular, it is necessary to study the role that pre-equilibrium effects play. Under which circumstances can pre-equilibrium contributions be neglected? How well can we estimate these contributions? What reactions minimize pre-equilibrium effects? What sort of experimental studies are needed to advance our understanding of pre-equilibrium decay?

3. **Implementation of the Surrogate method:** What are the tools and ingredients that are necessary to make the Surrogate method work? How reliable and accurate are these tools and ingredients? Some examples: Hauser-Feshbach codes, direct-reaction codes, pre-equilibrium codes, level-density formulae and tables, particle and gamma detector arrays, mass separators, etc.

4. **Applications and limitations:** What are the most suitable areas of application for the Surrogate method? How well can the method be expected to do? What are its limitations? What is the potential use of the method at Radioactive Beam Facilities? How does the Surrogate technique compare to other methods of extracting cross sections involving radioactive nuclei?

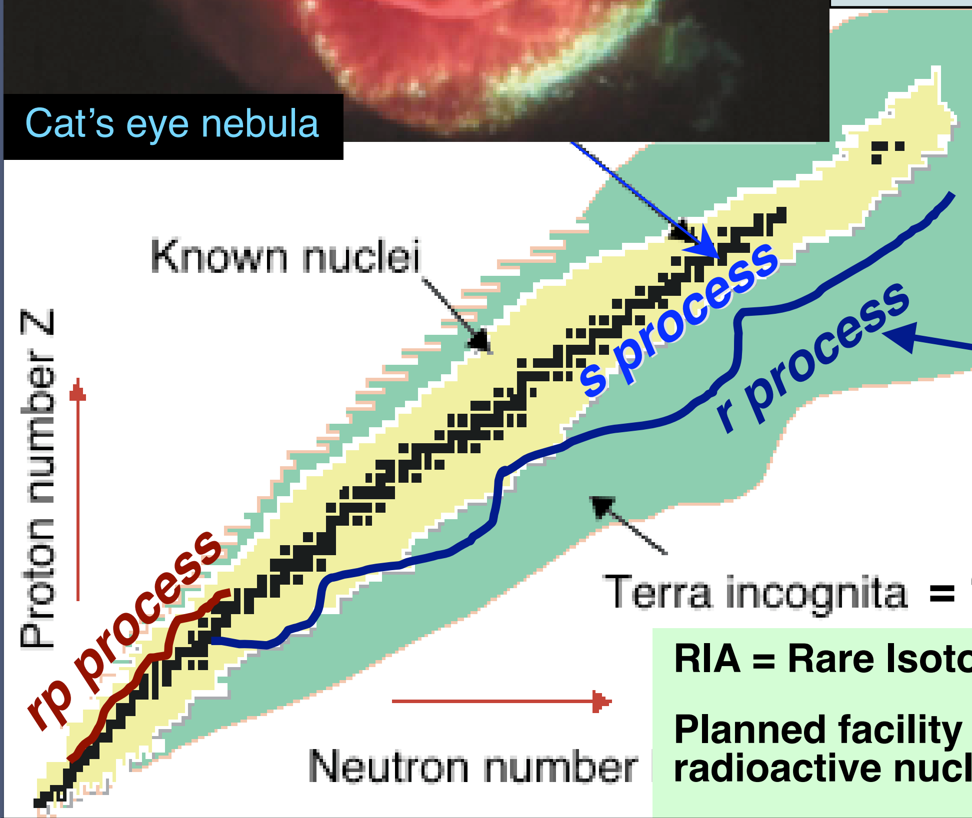
From the workshop program (page 4)

We hope to start some constructive discussions…

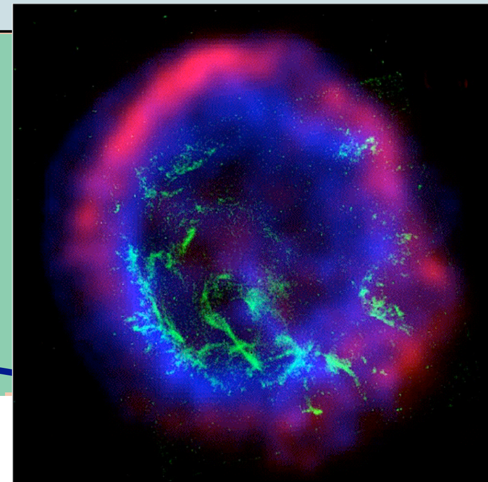
The future: RIA and the ‘Origin of the Heavy Elements’

Cat’s eye nebula

“How were the elements from iron to uranium made?” -- one of the ‘Eleven Science Questions for the New Century’
[*Connecting Quarks with the Cosmos*, Board on Physics and Astronomy, National Academies Press, 2003]



= ‘playground’ of RIA



Remnant of a supernova

Unresolved issues…

- **site of the r process? multiple sites?**
- **details of the supernova mechanism?**
- **mixing processes in red giants**
- **role of other processes?**

RIA = Rare Isotope Accelerator

Planned facility for studying radioactive nuclei

Fascinating connections between nuclear physics and astrophysics!

Understanding the origin of the heavy elements requires knowledge of reactions on unstable nuclei!

Appendix

Surrogate Nuclear Reactions – The Theory Effort at LLNL

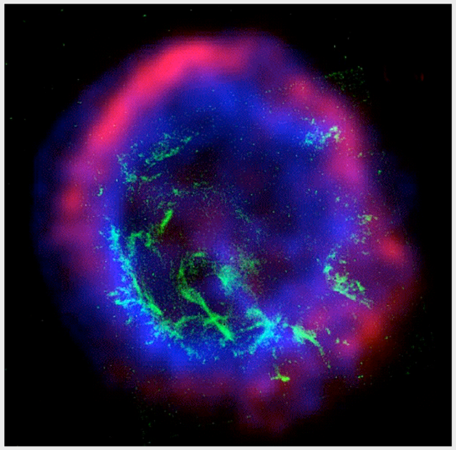
The Surrogate reaction technique can be employed to estimate reaction cross sections that cannot be measured directly. This is particularly relevant for reactions involving unstable nuclear species. The successful application of the Surrogate technique requires models that relate the reaction of interest to an alternative (‘Surrogate’) reaction which proceeds through the same compound system. Initial, limited, applications of the method in the rare earth and actinide regions show promise. In order to extend the applicability of the technique, new and improved theoretical tools and models become necessary. Efforts are underway at LLNL to provide a comprehensive framework for planning and analyzing Surrogate experiments. The applications will focus particularly on reactions involving unstable nuclei that play a key role in the production of the elements between iron and uranium. A brief overview over the theoretical ”Surrogate Nuclear Reactions” program at LLNL will be given. The main challenges to be addressed will be outlined and possible applications will be considered.

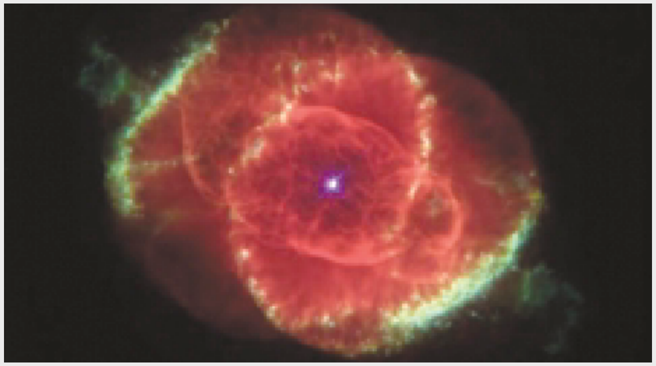
Abstract for the workshop “Nuclear Reactions on Unstable Nuclei” - Asilomar 2004

Explanation of Figures

Remnant of a supernova.

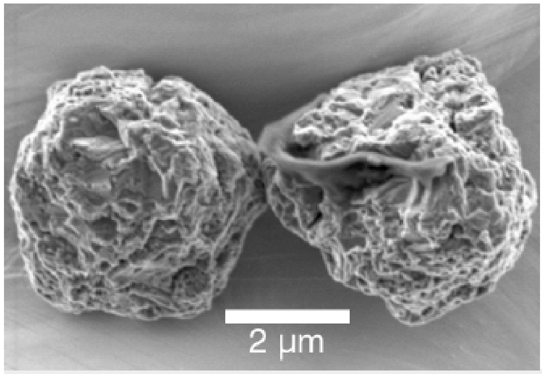
Supernovae are potential sites for r-process heavy-element synthesis.





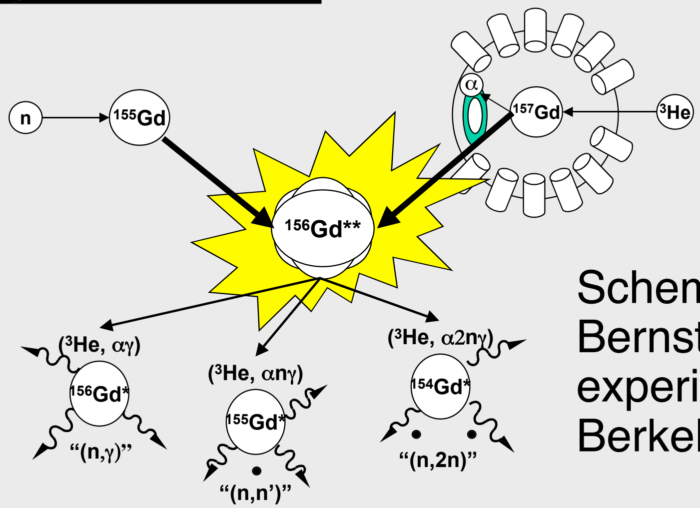
Death of a giant. Red giant stars form nebulae such as the Cat's Eye Nebula as they die, as strong winds blow off the star's surface. Our own sun will do this in a few billion years. Material coalescing in such nebulae may reach the Earth in the form of meteorites.

From DOE/NSF NSAC Long-range plan, 2002



Scanning electron microscope image of presolar silicon carbide grains from the Murchison meteorite. It is thought that these grains formed in the atmosphere of a red giant star, survived the formation of our solar system, and were transported to earth intact inside of this meteorite; hence, they preserve within them the signature of the environment in which they were created. The signature is the precisely measured relative abundances of isotopes of zirconium and molybdenum. Other grains or aggregates of grains contain other heavy elements. Their abundances can be compared to the signature calculated from various models for red giant stars. Precise neutron capture cross sections are required if such comparisons are to be used for improving stellar models.

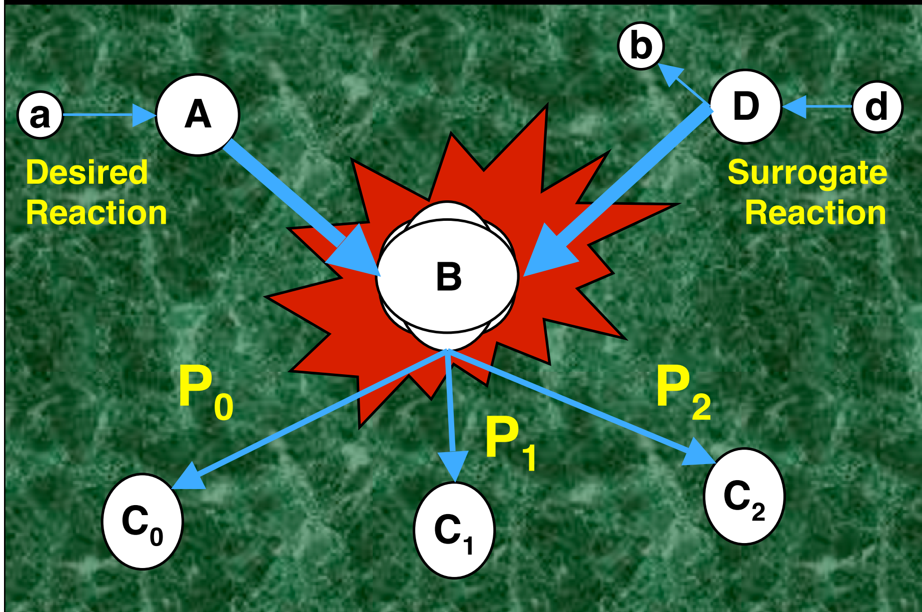
(Photo courtesy of Andrew Davis, University of Chicago.)



Schematic of Lee Bernstein's Surrogate experiment at Berkeley.

From "Opportunities in Nuclear Astrophysics" Town Meeting at Notre Dame, 1999

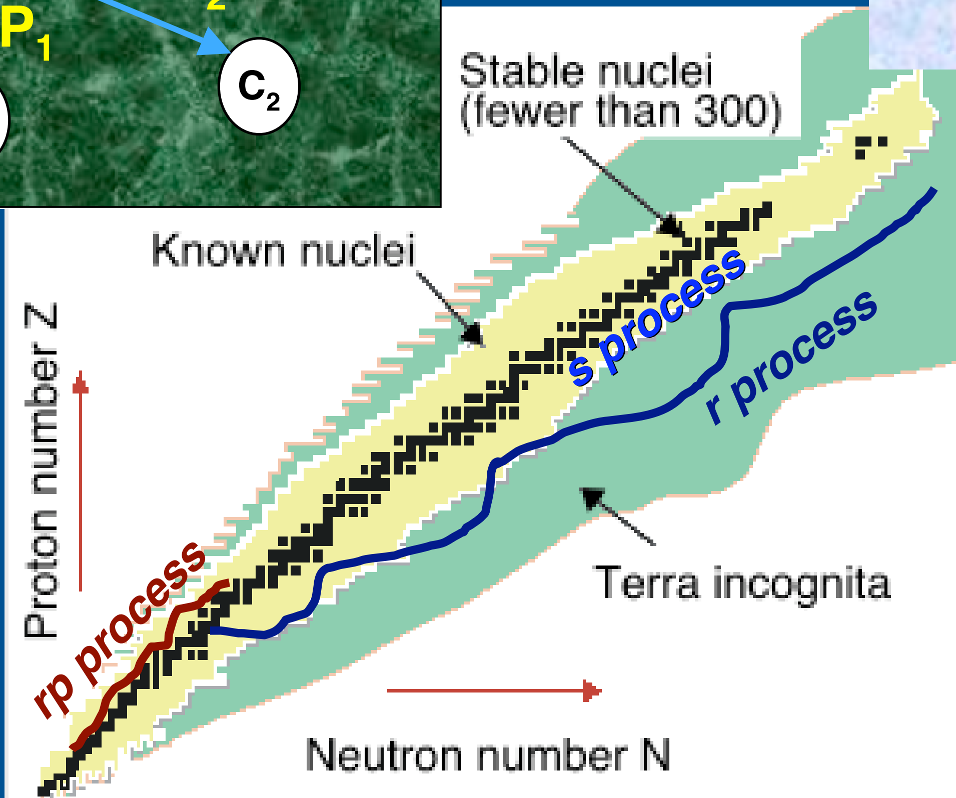
Nuclear Reactions on Unstable Nuclei and the Surrogate Reaction Technique

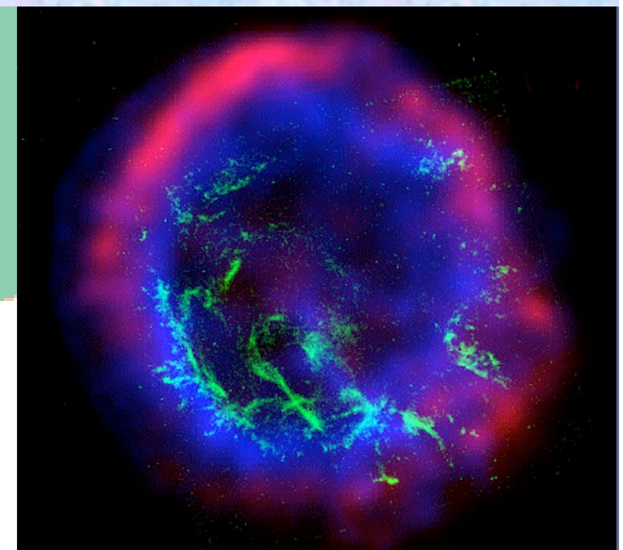


January 12-15, 2004
Asilomar Conference Grounds
Pacific Grove, California

Goal:

To initiate a discussion on exploring nuclear reactions involving short-lived species with the Surrogate method.





Advisory Committee:
Chip Britt (LLNL)
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Organizing Committee:
J. Escher , L. Ahle,
L. Bernstein, J. Church,
F. Dietrich, W. Younes, F. Mahler

http://www-pat.llnl.gov/ –> *'Events'*

Physics and Advanced Technologies